MASSACHUSETTS INSTITUTE OF TECHNOLOGY

METEOROLOGICAL COURSE

C. -G. Rossby, In Charge

PROFESSIONAL NOTES - NO. 7

ANALYSIS OF THE CUP ANEMOMETER

by

ATHELSTAN F. SPILHAUS

Cambridge, Massachusetts

1934

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INTRODUCTION

In the mass of literature on the Robinson Cup Anemometer many analytical and empirical equations have been suggested to describe the performance of this instrument. None of the purely analytical forms adequately consider the complicated aerodynamical processes upon which the action of the anemometer depends. Indeed, the single point upon which most investigators in the field agree is the futility of attempting any such purely theoretical treatment. The need for a systematic investigation of the controlling effect of arm length, cup size and number of cups was recognized by Patterson[1] and an excellent discussion of the problem from torque considerations is presented by him.

Recently large influences of a purely aerodynamic character not embraced by Patterson's method have been recognized by Dryden[2] and Grimminger.[3] It is possible to develop a semi-empirical equation whose parameters are in such a form as to enable them to be discussed according to the concepts of modern aerodynamics, and it will be the endeavour of the author in this monograph to present his various data in that form.

GENERAL FORM OF THE ANEMOMETER LAW

Empirical equations in the form of one or more terms of the power series

$$V = a_1 + b_1 v + c_1 v^2 + \cdots$$

(where V is the true wind velocity, v is the peripheral velocity of the cup centers and $a_1 b_1 c_1$ etc. are constants) have been used from time to time, but the usefulness of such a form is restricted to one anemometer for which the calibration curve is known. The constants cannot be related to the fundamental parameters of the instrument in general.

Lately Marvin[4] has employed an equation of hyperbolic form connecting V with N, the number of cup turns per unit travel of wind, such that

$$N = \frac{b(V - V_0)}{V + a},$$

where V_0 is the wind velocity at which the cups just cease to rotate. Here again a satisfactory relation between the constants a, b and the parameters of the anemometer was not obtained.

Marvin actually found that b depended on the length of the arms L alone for all the sizes of cups and arms which he considered. Now as b is the limiting value of N as $V \to \infty$ and $N = \frac{5280\, v}{2\pi L\, V}$ (for L in feet and N in turns per mile of wind) it is evident that b, if plotted against L, is merely

$$\frac{K}{L}\left(\frac{v}{V}\right)_{v \to \infty} \quad \text{vs. } L \qquad \text{(Marvin's Fig. 9)}$$

The small variations of $(v/V)_{V \to \infty}$ are obscured by this method of examination but it would appear that it is a function of L alone.

The ratio of the velocity v/V, however is nondimensional and can only be a function of L alone if L occurs in a non-dimensional parameter where the other factors happen to have been constants throughout the series of experimental tests.

It was decided in the present instance to employ an equation of the form

$$\left(\frac{V}{v} - h\right)\left(\frac{V}{V_0} - 1\right) = k.$$

This represents a rectangular hyperbola connecting the anemometer factor V/v with the true wind velocity V. Both the constants h and k are non-dimensional and it must therefore be possible to describe them with a finite number of non-dimensional parameters of the constants of the particular instrument. It is immediately evident that as $V \rightarrow \infty$, V/v tends to the asymptote h, thus

$$h = (V/v)_{v \rightarrow \infty} = K/Lb, \qquad (K = 5280/2\pi \text{ for Marvin's units*})$$

where b is Marvin's asymptotic value of N, and

$$k = \frac{h}{V_0}(a + V_0) = \frac{m^2}{2}.$$

These expressions for h and k give their relation to Marvin's constants a and b. An example of the hyperbolic law fitted to experimental calibration points is shown in Fig. 1.

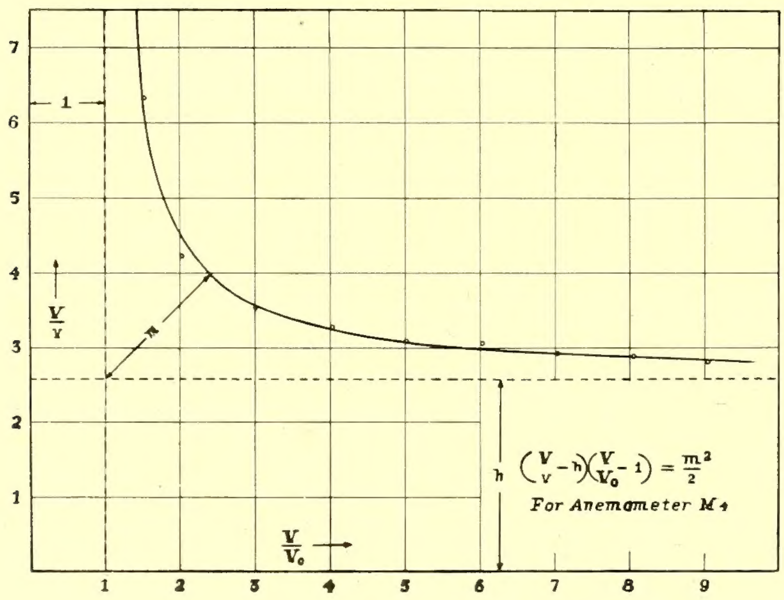

Fig. 1

* In the following, all quantities are expressed throughout in meters and meters per second.

DETERMINATION OF V_0

The influence of bearing friction on the operation of the anemometer is embodied in the term V_0 which may be regarded as the true wind velocity at which the cups turn so slowly ($v \rightarrow$zero) that the relative velocity can simply be taken as V_0.

v is, however, still assumed to be finite so that the mean normal force coefficient $\overline{C_N}$ on the cups can be found by integration over 180°.

Thus

$$\overline{C_N} = 1/\pi \int_0^\pi C_N d\alpha \qquad C_N = \frac{\text{Force normal to cups face}}{Aq}$$

A = area of cup face

q = dynamic pressure = $\frac{1}{2}\rho V^2$.

Brevoort and Joyner[5] have shown curves for C_N at various values of α from 0 to π and at various Reynolds' Numbers. If $\overline{C_N}$ is evaluated by mechanical integration from these curves (Fig. 6 of Ref. 5) it is found that

$$\overline{C_N} = A + BR$$

(where A and B are constants and R=Reynolds' Number) represents the variation of $\overline{C_N}$ with R very well up to $R = 32 \times 10^4$ (cf. Fig. 2.)

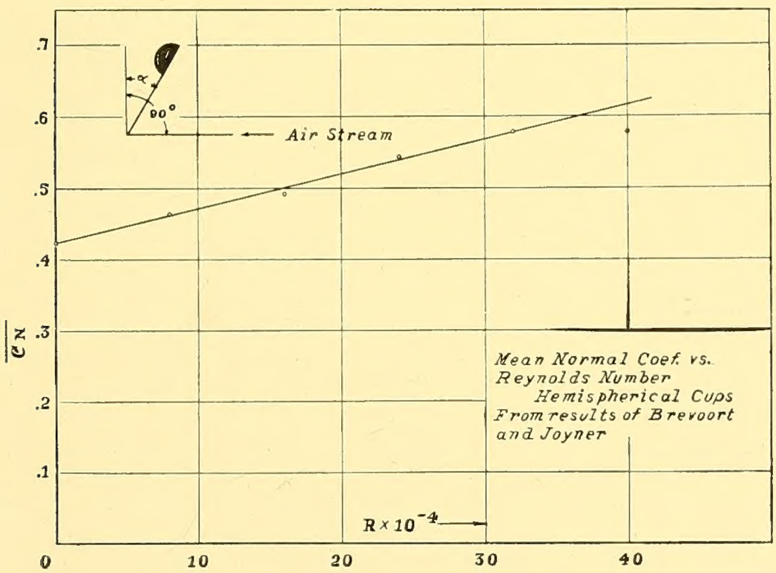

FIG. 2

Although this is interesting, for the purpose of evaluating V_0, which is never very great, BR is small and negligible in comparison with A. The condition when $v \rightarrow 0$ may be written

$$\eta \overline{C}_{N_{[R\to 0]}} \frac{\rho V_0^2}{2} \frac{\pi d^2}{4} \frac{D}{2} = T,$$

where η is the number of cups, d is the diameter of the cups, D is the diameter of the cup center orbit, and T is the dynamic frictional torque of the bearing which is substantially constant for a good ball bearing.

Then

$$V_0 = \sqrt{\frac{16T}{\eta \overline{C}_N \rho \pi d^2 D}}.$$

TABLE I

TESTS ON FOUR CUP ANEMOMETERS AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Index	d/D	d	D	V_0	h	k
A	.052	.031	.604	1.84	3.97	2.93
B	.1	.031	.31	2.57	3.13	3.03
C		.062	.62	.91	2.64	6.58
D	.2	.031	.155	3.63	2.76	1.77
E		.062	.310	1.28	2.19	6.43
F		.100	.500	.627	2.09	6.4
G		.127	.635	.438	1.915	12.2
H	.3	.031	0.103	4.45	2.59	1.93
I		.062	.2066	1.58	2.31	3.89
J		.100	.333	.77	2.21	3.9
K		.127	.423	.535	2.08	6.3
L	.4	.031	.0775	5.13	2.62	1.515
M		.100	.25	.89	2.34	3.62
N		.127	.3175	.62	2.15	6.15
O	.5	.100	.20	.99	2.33	1.875
P		.127	.254	.69	2.22	2.78
Q	.6	.127	.2116	.76	2.46	1.1
R	.7	.127	.181	.82	2.54	1.02
S	.85	.127	.149	.9	2.63	.33
T	.89	.031	.035	7.7	2.79	1.14

It is noted that this simple expression does not take into account the sheltering of one cup by another, although such shielding may be considerable, especially in a system where d/D approaches unity.

Then if V_0 is known, h and k can be evaluated from the experimental results, for each particular anemometer, by the method of least squares. Table I shows the values of h and k, evaluated from the test results, for different dimensions of cups and for different values of the "dissimilarity factor" d/D. These values are plotted against d/D and its reciprocal in Figs. 3 and 4 respectively.

TABLE I(a)

VALUES OF h AND k OBTAINED FROM MARVIN'S DATA

Index	d/D	d	D	V_0	$h=\frac{10,080}{Lb}$	$k=\frac{ha}{V_0}+1$	
1	.853	.1016	.119	.3	2.61	.2	
2	.59	.114	.193	.67	2.40	1.007	
	.64	.127	.199	.67	2.34	1.007	
3	.42	.1016	.242	.30	2.29	7.47	
	.42	.1016	.242	.30	2.29	7.47	
4	.41	.127	.261	.30	2.19	8.79	
5	.57	.152	.265	.30	2.3	6.52	
6	.375	.1016	.271	.30	2.26	8.85	
7	.417	.114	.275	.30	2.18	8.38	
8	.4	.127	.318	.67	2.17	3.94	3 cup Anemometers
	.4	.127	.317	.67	2.17	3.94	
9	.4	.127	.32	.30	2.3	8.06	
10	.34	.114	.333	.30	2.18	8.5	
	.34	.114	.333	.30	2.18	8.5	
11	.46	.152	.334	.30	2.2	10.65	
12	.30	.1016	.339	.30	2.2	10.65	
13	.30	.1016	.339	.30	2.23	12.8	
14	.356	.155	.435	.50	2.22	1.413	
15	.23	.1016	.437	.30	2.13	11.85	
	.26	.114	.437	.30	2.13	11.85	

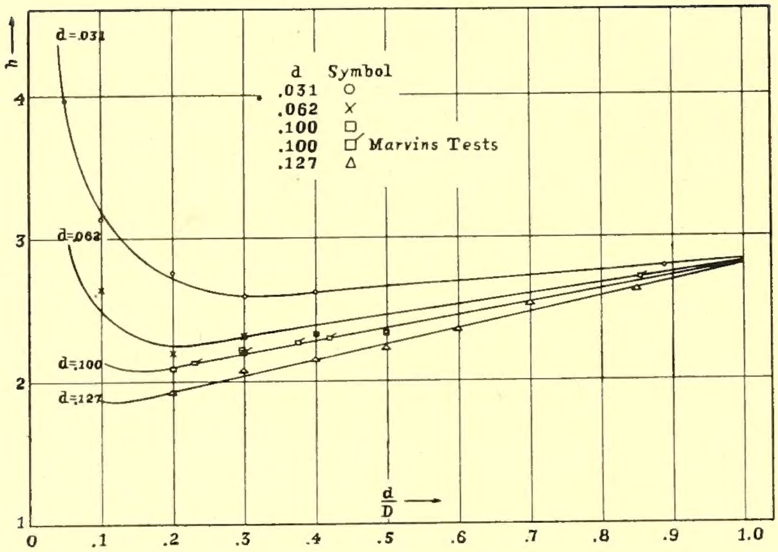
h
d=.031
d=.062
d=.100
d=.127
d Symbol
.031 ○
.062 ×
.100 □
.100 □ Marvins Tests
.127 △
d/D
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
1 2 3 4

Fig. 3

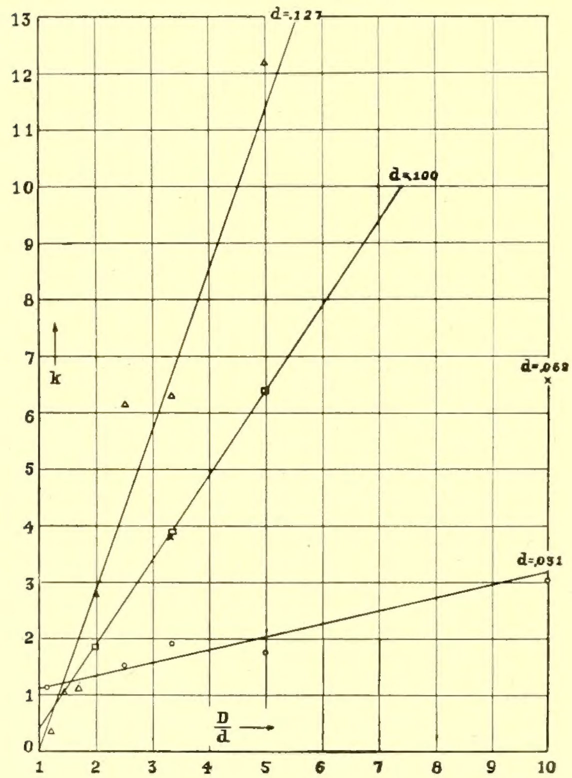
d=.127
d=.100
d=.062
d=.031
k
D/d
1 2 3 4 5 6 7 8 9 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13

Fig. 4

DISCUSSION OF THE PARAMETERS INFLUENCING h AND k

It is immediately apparent from figures 3 and 4 that the parameter d/D, which was chosen first of all because it seemed the most likely, is not the only controlling parameter but that both in the values of h and k there enters an independent "scale effect."

The scale effect on the factor k is easily accounted for by a combination of the separate effect of V_0 and the inherent turbulence of the air stream in which the anemometers were tested. Thus the effect of V_0 would be described in the form of a Reynolds Number dV_0/ν while the turbulence effect not accounted for by this Reynolds number could be expressed as the ratio λ/d, where λ is some length introduced to characterize the magnitude of the inherent air stream turbulence.

Table II

Harrington's Tests at Various Frictional Values

Instrument Constants $d=.115$; $D=.254$; $d/D=.453$; Beaded semiconical Cups

V_0	$\frac{d\,V_0}{\nu} \times 10^{-4}$	h	k
.272	.216	3.16	1.535
.904	.72	3.15	0.465
1.12	.89	3.11	0.625

Thus k is a function of the three parameters d/D, dV_0/ν and λ/d. The variation of k with dV_0/ν for d/D and λ/d constant is indicated by Harrington's tests[6] (Table II) on the same anemometer at various frictional torques. k appears to decrease with increase of the Reynolds Number. Also for d/D and dV_0/ν constant, tests made at the Bureau of Standards (Table III) indicate that k also decreases with increase of inherent air stream turbulence.* The tests available for the discussion of k are, however, insufficient for the separation of these two distinct scale effects.

Table III

Tests of Bureau of Standards with Different Turbulence Values

	d	d/D	V_0	h	k	Turbulence %
Cup wheel	.100	.292	.3	2.58	3.33	4.6
21	.100	.292	.3	2.55	7.38	0.7
Cup wheel	.100	.438	.37	2.82	2.42	0.7
22	Test results too irregular to be used.					4.6

The factor h may now be considered, and has been replotted in Fig. 5 against D alone. From this figure it is apparent that h is independent of the dissimilarity ratio d/D but in general, has only a pure scale effect.

* In their study on "The Effect of Turbulence,"[7] Millikan and Klein conclude that the lowest possible tunnel turbulence corresponds most nearly to conditions in the free atmosphere.

THE EFFECT OF THE ANEMOMETER ARMS

Deviations from the general law are shown by the dotted lines (Fig. 5) and represent the effect of the anemometer arms. For the smaller cup sizes the arms were of relatively greater thickness and presented a larger resistance (cf. also Patterson[1]) so that h will increase with a non-dimensional parameter involving the arm thickness (δ = diam. for cylindrical arms) and of the

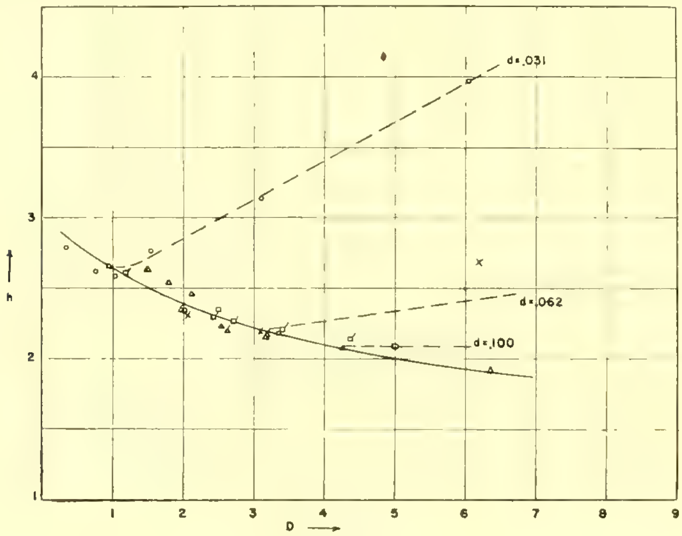

FIG. 5

form $\delta/d(D/d-1)$. This simple parameter is chosen as the ratio of the area of the arms exposed to the wind, $\delta(D-d)$, to the area of the cup face Kd^2. In Fig. 6 the deviation Δh of the value of h from the general law is shown as a function of $\delta/d(D/d-1)$ where Δh is the effect of the anemometer arms on the factor h.

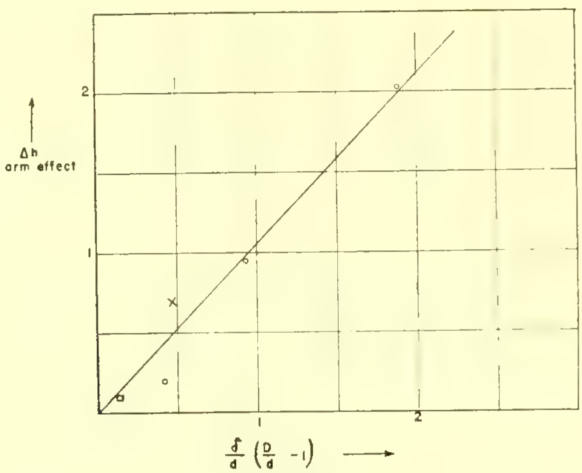

FIG. 6

It remains to explain this pure scale effect on h which was found previously by Marvin (cf. Page 3).

The Reynolds Number introduced in the discussion of k cannot enter here because evidently V_0 cannot have any effect as V becomes very great and h represents V/v as V approaches infinity. This is substantiated by Harrington's tests (Table II) where it is seen that h remains fairly constant over a great variation of V_0 (P. 9).

Neither is it plausible that any turbulence inherent in the wind tunnel flow could account for a scale effect such as this; for at the higher rotational velocities the anemometer creates its own turbulent whirl which would dominate over any initial turbulent character of the airstream. The results of tests made at the Bureau of Standards on Marvin s beaded cup anemometer reveal a very small percentual change of h for turbulence extremes of .7% and 4.6%. Table III.

The influence of the wind tunnel size which might have introduced such a scale effect has been shown to be negligibly small for the various sizes of wind tunnels which have been used for anemometer tests.

It is just conceivable that a Reynolds Number incorporating the velocity of sound might account for this scale effect but this would mean that very high velocities would have to be attained within the whirl set up by the anemometer. Radial exchange of momentum within this whirl would bring about the condition for the absence of vorticity $v_r r = \text{const.}$ where $v_r =$ velocity of whirl at any radius r, and thus v_r would increase inwards until it reached a limiting value. This explanation, however, seems rather inacceptable and it is hoped that experiments in a variable density wind tunnel may reveal the nature of this scale effect.

THE NUMBER OF CUPS

The discussion so far has been confined to the four cup anemometer but a certain number of experiments were carried out on anemometers having 3 and 2 cups in order to find out the variation of the various factors with the number of cups used.

Examination of the test results indicates that the factor h is substantially unaffected by the number of cups, all other dimensions being kept constant. k appears to be less for the 3 cup than for the 4 cup anemometer. Patterson[1] has noted this in his remark that the factor for the 3 cup anemometer appeared to approach the asymptote more quickly than that for the corresponding anemometer having 4 cups.

The variation is, however, not sufficiently significant to enter into the discussion of the relative merits of 3 or 4 cups. In this connection the point brought out by Fergusson[8] might be mentioned. Fergusson has repeatedly stressed the importance of sensitivity of the cup anemometer although this question has not been considered by other writers; if, as he states, the 3 cup is more sensitive it should be used in preference to the 4 cup.

ANEMOMETER WITH CONSTANT ERROR

For a bearing of known frictional torque the curves h and k which determine the calibration which would result by the use of various diameter cups and arm lengths have been obtained.

In any practical anemometer the indicating scale must be connected to the cup wheel by some mechanical means and the indicated velocity, V_i is given by $V_i = Fv$ where F is some gear train factor. It is now well known that, with a constant gear train factor F, it is impossible to have $V_i = V$ except at the one point where the line $V/v = F$ cuts the hyperbola $(V/v - h)(V/v_0 - 1) = k$.

The procedure up to the present has been to choose F in a rather arbitrary fashion so that it fitted fairly well over the range of speeds to be measured. Thus at low speeds V_i would be too low, the error decreasing up to the point $V/v = F$ and after that V_i would become too high and a variable correction would be applied depending on V_i. This is extremely cumbersome and it will be shown that, by suitably designing the anemometer, the error can be reduced to an additive constant over the entire range of velocities.

Consider the equation

$$(V/v - h)(V/V_0 - 1) = k.$$

If we arrange $h = F$ (the gear train factor), then

$$V_i = hv$$

and

$$V = \frac{V_i + V_0 \pm \sqrt{(V_i + V_0)^2 - 4(h - k)vV_0}}{2}.$$

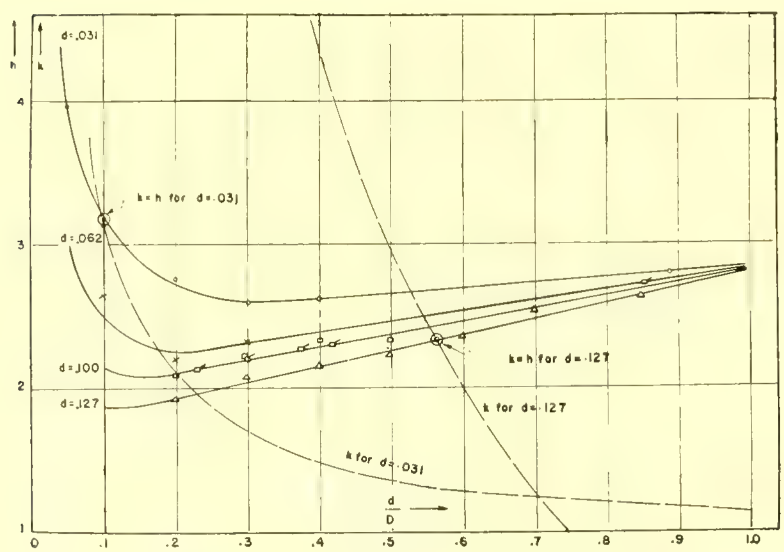

FIG. 7

The positive sign before the root is significant.

Then when

$$h > k \qquad \text{The error } V - V_i = f_n(v) < V_0$$

$$h = k \qquad V - V_i = V_0$$

$$h > k \qquad V - V_i = f_n(v) > V_0.$$

Thus if h and k are both plotted vs. d/D the points of intersection of the h and k curves for corresponding cup sizes will give the proportion of d/D for that cup size which will permit the instrument to operate according to the law $V - V_i = V_0$ (cf. Fig. 7).

Thus it is seen that by choosing the particular arm length given by this ratio a great simplification is introduced into the anemometer law whereby the simple addition of a constant to the indicated velocity gives the true wind velocity.

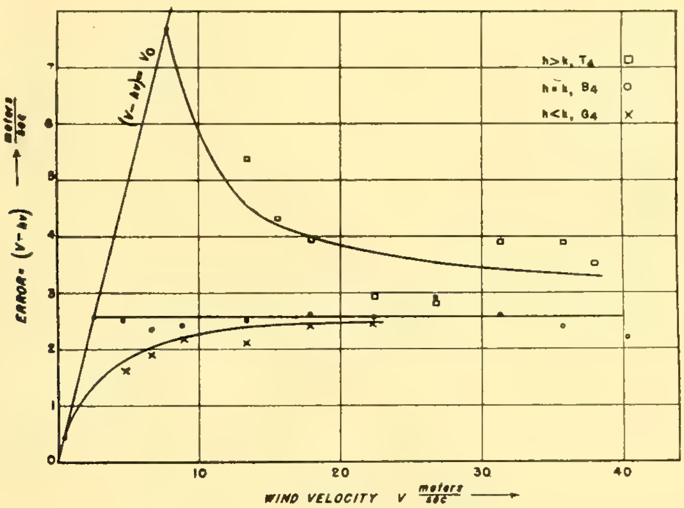

FIG. 8

The error curves shown in Figure 8 are taken for the three conditions of $h<k$, $h=k$ and $h>k$. As the errors are obtained by difference of two large quantities, extreme points for $h<k$ and $h>k$ are chosen.

$h > k$ is illustrated by the anemometer $d/D = .89$

for $d = .031$

$h < k$ is illustrated by the anemometer $d/D = .2$

for $d = .127$

$h = k$ is illustrated by the anemometer $d/D = .1$

for $d = .031$.

The theoretical error curves are obtained by employing the values of h, k and V_0 for the particular anemometer and computing V for various assigned values of $h \cdot v$. The experimental points are obtained from the observed values of V and v. (Table IV.)

TABLE IV

ERRORS

Instrument Constants		hv	Experimental V	Experimental $V-hv$	Theoretical V	Theoretical $V-hv$	
G_4	$d=.127$	3.3	4.92	1.62	5.16	1.86	
	$D=.635$	4.81	6.71	1.90	6.87	2.06	
	$V_0=.44$	6.79	8.95	2.16	8.96	2.17	$h<k$
	$k=12.2$	11.3	13.4	2.10	13.67	2.37	
	$h=1.94$	15.5	17.9	2.40	17.94	2.44	
		19.9	22.33	2.43	22.40	2.50	
T_4	$d=.031$	8.05	13.4	5.35	12.72	4.67	
	$D=.035$	11.3	15.6	4.3	15.55	4.25	
	$V_0=7.7$	13.95	17.9	3.95	17.95	4.00	
	$k=1.05$	19.4	22.33	2.93	23.05	3.65	$h>k$
	$h=2.79$	24.0	26.8	2.8	27.45	3.45	
		27.4	31.3	3.9	30.8	3.40	
		31.9	35.8	3.9	35.25	3.35	
		34.5	38.0	3.5	37.8	3.30	
B_4	$d=.031$	2.18	4.69	2.51			
	$D=.31$	4.4	6.71	2.31			
	$V_0=2.57$	6.55	8.95	2.4		Error	
	$h=3.13$	10.9	13.40	2.5		is	
	$k=3.13$	15.3	17.9	2.6		constant	
		19.8	22.33	2.53		$=2.57$	
		23.9	26.8	2.9			$h=k$
		29.7	31.3	2.6			
		33.4	35.8	2.4			
		38.1	40.3	2.2			

The theoretical curves are checked fairly well considering that a small percentual error in measurement appears greatly magnified in the error values. It is thought that these curves bring out the fact that for any anemometer a constant additive error can be obtained by correct proportioning of the arms to the cups for any given bearing.

Although for the small cups ($d=.031$) the dissimilarity ratio d/D for the point $h=k$ is 0.1 and this would mean an unusually slender anemometer; for the large cups ($d=.127$) the curve shows that the point $h=k$ would fall in the neighborhood of $d/D=.6$, and this would be a reasonable type of anemometer to use.

The ratio d/D of the cup system which would appear to prescribe to the law $V-V_i=V_0$, for the Standard Weather Bureau bearing and for cups $d=.100$, is in the neighborhood of $d/D=.7$. This value was obtained in the manner outlined above from the values of h and k from Marvin's data (Table Ia).

From the extremely scant data on the beaded hemispherical cup ($d=.100$) the ratio d/D for $h=k$ appears to lie around a value of .5, this being estimated from the data in Table III at .7% turbulence which is low enough according to considerations in the footnote on p. 9, to approximate free air conditions.

APPENDIX

Experimental Procedure

The wind tunnel tests were conducted in a routine manner in the 5 ft. wind tunnel at Massachusetts Institute of Technology. The true wind velocity was measured by means of a calibrated side plate while the rotational speed of the anemometer was given by a counter on the anemometer shaft in conjunction with a stop watch. These tests could be made at wind velocities up to about 40 m/sec. while the slowest velocity available in the tunnel was in the neighbourhood of 4.5 m./sec.

Due to the importance of the frictional term V_0 an attempt was made to determine V_0 experimentally in order to check the values given by the formula on page 6. For this purpose a whirling arm was not considered satisfactory and instead a carriage was arranged with a 30 meter run. It was propelled by an endless rope driven by an electric motor such that the speed of the carriage could be varied from zero to 3 m./sec. A considerable number of determinations of V_0 were made by the use of this simple device. These, however, showed considerable irregularity but served to indicate that the values obtained by the formula

$$V_0 = \sqrt{\frac{16T}{n\overline{C}_n p \pi d^2 D}}$$

were good mean values.

The dynamic frictional torque T of the bearing and counter used with all the anemometers was found by a dynamometer method to be about .08 gram-meters, and this value has been used throughout for computing V_0.

With V_0 known in the formula

$$\left(\frac{V}{v} - h\right)\left(\frac{V}{V_0} - 1\right) = k,$$

the simultaneous equations for the determination of h and k by the Method of Least Squares are

$$\begin{cases} \sum p_n q_n = h \sum q_n^2 + c \sum q_n \\ \sum p_n \quad - h \sum q_n = c \cdot n \end{cases}$$

where

$$\begin{cases} p_n = \dfrac{V}{v}(V - V_0) \\ q_n = (V - V_0) \\ c = kV_0. \end{cases}$$

The complete results are appended here.

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Tests of Anemometers

Index	Instrument constants	V	v	V/v	h	k
A_4	$d=$ .031	4.25	.715	5.95		
	$D=$ .604	6.71	1.36	4.94		
	$d/D=$ .0515	8.95	1.915	4.67		
		13.4	3.02	4.44		
		17.9	4.05	4.42	3.97	2.93
	$V_0=1.84$	22.33	5.22	4.28		
		26.8	6.27	4.28		
		31.3	7.48	4.19		
		35.8	8.71	4.11		
		40.3	9.97	4.05		
T_4	$d=$ .031	13.4	2.88	4.66		
	$D=$ .035	15.6	4.05	3.86		
		17.9	5.00	3.58		
	$d/D=$ .89	22.33	6.97	3.35		
		26.8	8.6	3.12	2.79	1.14
	$V_0=7.1$	31.3	9.83	3.18		
		35.8	11.45	3.13		
		38.0	12.35	3.08		
B_4	$d=$ .031	4.69	.696	6.75		
	$D=$ .31	6.71	1.403	4.78		
	$d/D=$ .1	8.95	2.09	4.29		
		13.4	3.48	3.85		
		17.9	4.88	3.67		
	$V_0=2.57$	22.33	6.32	3.54	3.13	3.03
		26.8	7.65	3.51		
		31.3	9.17	3.41		
		35.8	10.69	3.35		
		40.3	12.18	3.31		
C_4	$d=$ .062	5.14	1.487	3.45		
	$D=$ .62	6.71	1.89	3.55		
	$d/D=$ .1	8.95	2.61	3.43		
		13.4	4.17	3.22		
		17.9	5.74	3.12	2.64	6.58
	$V_0=$ .91	22.33	7.48	2.99		
		26.8	9.42	2.85		
		31.3	11.35	2.76		
D_4	$d=$ .031	6.71	.909	7.36		
	$D=$ .155	8.95	2.03	4.41		
	$d/D=$ .2	13.4	3.76	3.56		
		17.9	5.39	3.32		
		22.33	7.00	3.185	2.76	1.77
	$V_0=3.63$	26.8	8.6	3.115		
		31.3	10.44	2.995		
		25.8	12.02	2.975		
		40.3	13.72	2.935		
E_4	$d=$ .062	5.15	1.51	3.41		
	$D=$ .310	6.71	1.975	3.4		
	$d/D=$ .2	8.95	2.82	3.17		
		13.4	4.39	3.05		
		17.9	6.14	2.915	2.19	6.43
	$V_0=1.28$	22.33	8.17	2.73		
		26.8	10.6	2.527		
		31.3	12.94	2.42		
		35.8	15.15	2.36		

Index	Instrument constants	V	v	V/v	h	k
E_2	$d=$ .062	4.47	1.08	4.13		
	$D=$ .31	6.71	1.93	3.48		
	$d/D=$ .2	8.95	2.76	3.24		
		13.4	4.4	3.05	2.26	5.71
	$V_0=1.81$	17.9	6.09	2.94		
		22.33	8.01	2.91		
		26.8	9.94	2.7		
		31.3	11.9	2.63		
G_4	$d=$ .127	4.92	1.7	2.89		
	$D=$ .635	6.71	2.48	2.71		
	$d/D=$ .2	8.95	3.49	2.56	1.915	12.2
		13.4	5.81	2.31		
	$V_0=$ .445	17.9	7.98	2.24		
		22.33	10.28	2.17		
H_4	$d=$ .031	5.475	.513	10.7		
	$D=$ .103	6.71	1.055	6.35		
	$d/D=$ .3	8.45	2.12	4.22		
		13.4	3.82	3.52		
	$V_0=4.45$	17.9	5.47	3.28		
		22.33	7.2	3.10	2.59	1.93
		26.8	8.71	3.08		
		31.3	10.8	2.9		
		35.8	12.48	2.87		
		40.3	14.4	2.8		
G_2	$d=$ .127	4.7	1.62	2.9		
	$D=$ .635	6.71	2.51	2.67		
	$d/D=$ .2	8.95	3.41	2.63	2.03	6.72
		13.4	5.75	2.33		
	$V_0=$ .71	17.9	7.9	2.27		
		22.33	9.95	2.24		
K_4	$d=$ .127	4.92	1.75	2.81		
	$D=$ .423	6.71	2.56	2.62		
	$d/D=$ .3	8.95	3.6	2.48		
		13.4	5.67	2.36	2.08	6.3
	$V_0=$ .445	17.9	7.8	2.29		
		22.33	10.0	2.233		
J_4	$d=$ .1	4.92	1.68	2.93		
	$D=$ .333	6.71	2.42	2.77		
	$d/D=$ .3	8.95	3.41	2.63		
		13.4	5.4	2.48		
		17.9	7.52	2.38	2.21	3.9
	$V_0=$ .77	22.33	9.6	2.32		
		26.8	11.6	2.31		
		31.3	13.6	2.3		
		35.8	15.6	2.29		
F_4	$d=$ .1	4.69	1.58	3.01		
	$D=$ .5	6.71	2.36	2.84		
	$d/D=$ .2	8.95	3.35	2.67		
		13.4	5.5	2.44	2.09	6.4
	$V_0=$ .588	17.9	7.8	2.3		
		22.33	10.0	2.233		
		26.8	11.9	2.25		

Index	Instrument constants	V	v	V/v	h	k
O_4	$d=.100$	4.69	1.63	2.87		
	$D=.200$	6.71	2.51	2.67		
	$d/D=.5$	8.95	3.54	2.53		
		13.4	5.45	2.45	2.33	1.815
	$V_0=.99$	17.9	7.34	2.44		
		22.33	9.28	2.40		
		31.3	13.0	2.40		
Q_4	$d=.127$	5.15	1.921	2.6		
	$D=.2116$	6.71	2.56	2.62		
	$d/D=.6$	8.95	3.52	2.55	2.46	1.1
		13.4	5.3	2.53		
	$V_0=.76$	17.9	7.12	2.52		
		22.33	8.95	2.49		
R_4	$d=.127$	4.69	1.705	2.75		
	$D=.181$	6.71	2.54	2.64		
	$d/D=.7$	8.95	3.42	2.61	2.54	1.02
		13.4	5.11	2.62		
	$V_0=.82$	17.9	6.9	2.60		
		22.33	8.65	2.58		
S_4	$d=.127$	5.15	1.85	2.78		
	$D=.149$	6.71	2.49	2.69		
	$d/D=.85$	8.95	3.37	2.65	2.63	.33
		13.4	5.03	2.66		
	$V_0=.9$	17.9	6.77	2.65		
		22.33	8.48	2.64		
L_4	$d=.031$	6.71	.736	9.12		
	$D=.0775$	8.95	2.055	4.35		
	$d/D=.4$	13.4	3.83	3.5		
		17.9	5.61	3.2		
		22.33	7.37	3.03	2.62	1.515
	$V_0=5.13$	26.8	8.93	3.00		
		31.3	10.8	2.9		
		35.8	12.45	2.88		
		40.3	14.15	2.84		
L_3	$d=.031$	(5.14	.488	10.5)		
	$D=.0775$	6.71	1.076	6.23		
	$d/D=.4$	8.95	1.98	4.51		
		13.4	3.85	3.48	2.73	.614
	$V_0=6.3$	17.9	5.71	3.14		
		22.33	7.4	3.02		
		26.8	9.18	2.92		
		31.3	11.1	2.83		
D_2	$d=.031$	6.71	.84	8.0		
	$D=.155$	8.95	1.77	5.06		
	$d/D=.2$	13.4	3.425	3.91		
		17.9	5.08	3.53	2.76	1.68
		22.33	6.72	3.33		
	$V_0=5.3$	26.8	8.35	3.21		
		31.3	10.1	3.11		
		35.8	11.83	3.03		

Index	Instrument constants	V	v	V/v	h	k
B_3	$d=.031$	4.92	.762	6.47		
	$D=.31$	6.71	1.28	5.24		
	$d/D=.1$	8.95	2.015	4.45		
		13.4	3.39	3.95		
		17.9	4.78	3.75	3.30	1.95
	$V_0=2.96$	22.33	6.17	3.63		
		26.8	7.5	3.58		
		31.3	9.16	3.42		
		35.8	10.4	3.44		
		40.3	11.88	3.39		
C_3	$d=.062$	4.92	1.333	3.69		
	$D=.62$	6.71	1.855	3.62		
	$d/D=.1$	8.95	2.57	3.48		
		13.4	3.82	3.51	2.49	10.4
	$V_0=1.05$	17.9	5.83	3.08		
		22.33	7.46	3.00		
		26.8	9.5	2.82		
		31.3	10.53	2.97		
M_4	$d=.100$	4.91	1.65	2.97		
	$D=.25$	6.71	2.32	2.9		
	$d/D=.4$	8.95	3.29	2.72		
		13.4	5.07	2.65		
		17.9	7.01	2.56	2.34	3.62
	$V_0=.89$	22.33	9.00	2.41		
		26.8	10.8	2.48		
		31.3	13.0	2.41		
		35.8	14.75	2.43		
I_4	$d=.062$	5.15	1.53	3.36		
	$D=.2066$	6.11	2.08	3.23		
	$d/D=.3$	8.95	2.85	3.14		
		13.4	4.5	2.98		
		17.9	6.35	2.82	2.31	3.89
	$V_0=1.57$	22.33	8.39	2.67		
		26.8	10.3	2.60		
		31.3	12.54	2.49		
		35.8	14.65	2.44		
Q_3	$d=.127$	5.15	1.94	2.65		
	$D=.2116$	6.71	2.565	2.62		
	$d/D=.6$	8.95	3.565	2.51	2.43	1.14
		13.4	5.34	2.51		
		17.9	7.2	2.485		
	$V_0=.88$	22.33	9.02	2.47		
P_4	$d=.127$	5.36	2.0	2.68		
	$D=.254$	6.71	2.66	2.52		
	$d/D=.5$	8.95	3.65	2.45	2.22	2.78
		13.4	5.64	2.38		
		17.9	7.65	2.34		
	$V_0=.69$	22.33	9.68	2.31		

Index	Instrument constants	V	v	V/v	h	k
V_4	$d=$ .031	6.71	1.21	5.55		
	$D=$ .062	8.95	2.15	4.16		
	$d/D=$ .5	13.4	3.76	3.56		
		17.9	5.42	3.31	2.88	0.59
	$V_0=5.75$	22.33	7.04	3.17		
		26.8	8.64	3.10		
		31.3	10.3	3.03		
		35.8	11.86	3.02		
U_4	$d=$ .062	4.47	1.28	3.49		
	$D=$ .155	6.71	1.97	3.41		
	$d/D=$ .4	8.95	2.77	3.23		
		13.4	4.35	3.08		
		17.9	6.12	2.93	2.565	2.515
	$V_0=1.81$	22.33	7.95	2.81		
		26.8	9.63	2.78		
		31.3	11.5	2.71		
		35.8	13.4	2.67		
N_4	$d=$ .127	4.47	1.55	2.87		
	$D=$ .3175	6.71	2.41	2.78		
	$d/D=$ .4	8.95	3.39	2.64		
		13.4	5.43	2.47	2.15	6.15
		17.9	1.52	2.38		
	$V_0=$ .62	22.33	9.66	2.32		
		26.8	11.67	2.30		
D_3	$d=$ .031	5.01	.557	9.0		
	$D=$ .155	6.71	1.243	5.4		
	$d/D=$ .2	8.95	2.07	4.32		
		13.4	3.73	3.59		
	$V_0=$?	17.9	5.37	3.33	?	?
		22.33	7.08	3.15		
		26.8	8.7	3.08		
		31.3	10.48	2.98		
		35.8	12.13	2.95		
		40.3	13.92	2.89		

Index	Instrument constants	V	v	V/v	h	k
N_2	$d=$ .127	4.91	1.77	2.77		
	$D=$ .3175	6.71	2.47	2.72		
	$d/D=$ .4	8.95	3.48	2.57	2.21	3.02
		13.4	5.48	2.45		
		17.9	7.58	2.36		
	$V_0=$ .87	22.33	9.7	2.30		
L_2	$d=$ .031	(6.71	.143	47.1)		
	$D=$ .0775	8.95	1.36	6.59		
	$d/D=$ .4	13.4	3.24	4.14		
		17.9	4.9	3.66	2.71	1.22
		22.33	6.78	3.30		
	$V_0=7.25$	26.8	8.28	3.24		
		31.3	10.3	3.03		
		35.8	11.9	3.00		
N_3	$d=$ .127	5.03	1.94	2.59		
	$D=$ .3175	6.71	2.57	2.61		
	$d/D=$ .4	8.95	3.64	2.46	2.2	2.85
		13.4	5.66	2.37		
		17.9	7.7	2.33		
	$V_0=$ .72	22.33	9.8	2.28		
G_3	$d=$ .127	4.47	1.58	2.83		
	$D=$ .635	6.71	2.55	2.63		
	$d/D=$ .2	8.95	3.49	2.57		
		13.4	5.66	2.37	1.89	12
	$V_0=$ .51	17.9	7.96	2.25		
		22.33	10.2	2.19		

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